

Review

Floodplains and Complex Adaptive Systems—Perspectives on Connecting the Dots in Flood Risk Assessment with Coupled Component Models

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Abstract: Floodplains, as seen from the flood risk management perspective, are composed of co-evolving natural and human systems. Both flood processes (that is, the hazard) and the values at risk (that is, settlements and infrastructure built in hazardous areas) are dynamically changing over time and influence each other. These changes influence future risk pathways. The co-evolution of all of these drivers for changes in flood risk could lead to emergent behavior. Hence, complexity theory and systems science can provide a sound theoretical framework for flood risk management in the 21st century. This review aims at providing an entry point for modelers in flood risk research to consider floodplains as complex adaptive systems. For the systems science community, the actual problems and approaches in the flood risk research community are summarized. Finally, an outlook is given on potential future coupled component modeling approaches that aims at bringing together both disciplines.

Keywords: flood risk; floodplains; sensitivity analysis; coupled component modeling; complex adaptive systems

1. Introduction

Floods are one of the most damaging natural hazards, accounting for a majority of all economic losses from natural events worldwide [1]. Managing flood risks requires knowledge about hazardous processes and their impacts. Hence, risks resulting from floods are defined as functions of the probability of a flood event or scenario, respectively, and the related extent of damage [2,3]. The latter is computed in most cases by a function of the monetary value of the object affected by the flood and its vulnerability against the magnitude of the process scenario. In floodplains, these main factors of flood risk, the flood process, and the values at risk meet each other locally. From a physical perspective, floodplains are defined as areas of land adjacent to and formed by flowing water in times of floods. In addition, from a socioeconomic perspective, floodplains provide land for settlement, infrastructure, and other human activities. Floodplains and the main drivers for flood risks are evolving over time. Consequently, in natural hazards and risk research, an actual change in the paradigms can be observed. Risks are being more frequently analyzed from a dynamic rather than a static perspective [4,5]. Hence, many studies are dealing with changes of natural risks over recent decades and centuries [2,6–10]. In addition, research on climate changes and its impact is the focus of future changes in risks [11–20]. A few studies consider both the impacts of climatic changes to river flows and the future dynamics in the values at risk [21–26]. As drivers for changes in risk are not only varying in time, recent studies extend the dynamic framework of risk analysis toward a spatiotemporal framework [27–34]. Herein, the drivers of flood risk vary in space and time. Consequently, a few studies adopted the system dynamics approach to a spatial system dynamics approach for water resources systems and flood

risk analyses [35–37]. Beside flood risk research, system dynamics modeling is also becoming an increasingly attractive approach in social sciences and earth system modeling [38–42].

In summary, the built environment in floodplains, whether the settlement area or the river channel, is subject to changes and co-evolutionary dynamics in both spheres. Floodplains are influenced by flood events and subsequent disruptive changes in the society, by governmental decisions as adaptation to these flood events, and individual agents. These co-evolutionary dynamics in the drivers for changes in flood risk influence future risk pathways, and could lead to emergent behavior. Hence, complexity theory and systems science potentially provide a sound theoretical framework for flood risk management as postulated by Helbing et al. [43] for other risks.

This short review aims at summarizing recent attempts in analyzing and modeling spatiotemporal changes in flood risk from a complex systems perspective and at giving an explorative outlook of future perspectives in considering floodplains as complex adaptive systems. With this, I am aiming at providing a summary of the prospective approaches for modeling the co-evolutionary dynamics and emergent behavior of floodplains and thus, an entry point for flood risk modelers to consider floodplains as complex adaptive systems. Moreover, I am aiming at providing a collection of relevant literature from the flood risk research community, and thus an entry point for the systems science community into flood risk research. The focus is placed on the approaches for modeling the co-evolutionary and spatiotemporal dynamics in the evolution of flood risks in floodplains.

2. Main Drivers of Evolving Risks in Floodplains

The spatiotemporal evolution of flood risk in floodplains is composed of several drivers that are intertwined with each other. In a reductionist approach, flood risk research is focusing on a single aspect of flood risk and their changes in space and time. However, constructivist perspectives in flood risk research are rather rare, and are more frequently present in the systems sciences. In this paper, I will summarize the main drivers of evolving flood risks in floodplains.

2.1. Changes in Flood Processes

Floods are either caused directly by rainfall onto the system under investigation (pluvial floods and surface water floods, for example) or by falling onto river catchments, resulting in a catchment outflow. The latter causes floods in downstream floodplains (riverine floods and lake floods). Thus, the boundary condition of floods in floodplains can either be rainfall, river flows, or both. Consequently, changes in flood processes, that is, changes in the frequency and magnitude of floods, are determined by these external influencing factors. In many studies, the changes in rainfall frequency and intensity are investigated, with a special focus on the effects of climatic changes [44,45]. In addition, changes in the incoming flow hydrographs are drivers of change in floodplains [46–48]. In mountainous areas, flood losses are also influenced by sediment transport and deposition processes [49].

However, the rivers themselves and their floodplains change over time [50–53]. These can be natural and gradual changes in the river morphodynamics and flood regime [54–57], changes in the adjacent vegetation [58], or disruptive changes by flood events [59], for example by levee failures [60]. Last but not least, anthropogenic interventions are more or less the most relevant driver of flood risk in a floodplain; that is, the construction of flood defenses such as levees and dams [61–63] or river restoration projects [64–66]. Furthermore, the construction of levees as flood protection measures in one floodplain can have adverse effects in downstream floodplains [67–71], and thus result in trade-offs between upstream and downstream floodplains [72,73]. Reviews on the impacts of land use changes and regulations on floods are given by Rogger et al. [74], Burby et al. [75], and O’Connell et al. [76]. Moreover, floodplains can be affected by land subsidence due to drainage or groundwater extraction. This results in increasing flood hazards and consequently, increasing flood risk [77].

2.2. Changes in Exposure and Vulnerability

In addition to changes in the natural environment (that is, the fluvial aspect of the floodplain), flood risks also change due to variations in the exposed values at risk and in their vulnerability. First of all, one of the most relevant drivers of flood risk is the increase in the values that are at risk due to economic development [78,79]. The growing of settlements and thus, the increase of residential buildings is related to population growth [80]. With it, the infrastructure increases as well. Infrastructure failures have wider impacts on the socioeconomic systems, and thus exhibit relevant interdependencies [81–84]. In economically active areas, floodplains are increasingly occupied by production facilities, as these require relatively flat compound areas for their construction that are not available in hilly areas [85]. Recent studies show that the number of buildings potentially affected by floods increased by up to 700% in the last century [31,78]. With economic development, the objects at risk and the infrastructure in the floodplains increase in terms of monetary value. This and higher object vulnerabilities [86,87] result in increased flood risks. Both factors compete with the opposing drivers of flood risk reduction measures by individuals and the public.

2.3. Adaptation in Governance

Changes in exposure and vulnerability are influenced by the action of individuals and by governmental interventions and regulations. On the one hand, local governments regulate land use with planning instruments. In several countries, the occupation and utilization of areas potentially affected by floods are not allowed or restricted. Moreover, governmental institutions and legislative entities are defining the basic principles and legislative frameworks for spatial planning in floodplains. On the other hand, land use regulations are binding the actions of the individuals and businesses. Hence, both the actions of individual agents and the public composed by a collection of agents result in the key interfering driving forces for changes in flood risk [88]. Often, the actions of individuals and governments are an adaptation to flooding events [89–92]. When a flood affects a relevant share of a house or the infrastructure of the floodplain, individuals urge the government to act. As a reaction to the flood event and requests by the population, the local government invests in flood protection measures [93–95]. If many communities are affected, the regional or national governments react by adapting the legislative or financial framework for flood risk management [96–99]. Individuals experiencing a flood event become aware and sensible to the hazard, and adapt by protecting their homes and workplaces from floods with object-based flood protection measures [100,101]. Moreover, governments try to inform and to sensitize residents in floodplains by aiming at increasing risk awareness [102]. These adaptations can be seen as social learning. Consequently, the following flood event will result in fewer losses. Hence, the vulnerability of values at risk and socioeconomic activities in floodplains might decrease due to the adaptation measures. Overall, this complexity calls for adaptive flood risk management strategies and integrative governance [103–117].

3. Characterization of Floodplains from the Viewpoint of Complex Adaptive Systems

Flood risk—as a quantitative variable of hazard, exposure, and vulnerability—is evolving in space and time. However, the quantification of flood risk in terms of expected losses in a specified time period summarizes all of the factors into one lumped variable. As the single factors in the risk formula are supposed to be co-evolutionary dynamics, it is interesting to have a look at the spatiotemporal evolution of the single drivers first and second to the evolution of the floodplain as a whole. The classical risk formula and the approaches in risk analyses enable a monitoring of the temporal development of the risks by periodically repeating a risk analysis [118]. However, these approaches do not provide a theoretical framework for a deeper understanding and for delineating management options from the behavior of the floodplain, including all drivers of change. As shown in Section 2, the factors influencing flood risk exhibit co-evolutionary dynamics with positive and negative feedback between each other. Moreover, signals from the natural process shaping floodplains as well as information

processing between the local human agents and its collective in the form of governmental institutions in the floodplain lead to the complex behavior of a floodplain. Both the natural and the human systems adapt their behavior after flood events. The social system changes their behavior by learning from accidents and continuously adapting flood risk management strategies. Consequently, this adaptation leads to an emerging behavior of floodplains. Behavior in terms of vulnerability against floods and resilience changes remarkably with time. Following the overall complexity of the co-evolutionary dynamics in the drivers of flood risk and the emergent behavior, floodplains can be defined as complex adaptive systems [119,120]. As the actions of the individuals are difficult to predict, the future development paths of such a complex system as floodplains are difficult to predict as well. Hence, complex systems science might provide a helpful theoretical framework for the analysis and simulation of future development pathways of floodplains. However, the identification of emergent behavior, self-organization, and adaptation, as well as mapping complexity, remain a key challenge in flood risk research [121–124].

4. Prospective Approaches in Modeling Co-Evolutionary Dynamics in Floodplains

As the co-evolution of natural–human systems became more evident recently, the disciplines involved in flood risk research tried to collaborate with social sciences to implement human behavior in their models for analysis and prediction. There are mainly two research foci to mention in regard to the co-evolutionary dynamics in floodplains and the interactions between human and natural systems: the coupled human–natural systems approach, and the socio-hydrology approach [125]. The latter is a sub-discipline of socio-ecological systems research [126].

The research topic “coupled human–natural systems” (CHANS) mainly focus on wildlife habitats and landscape evolution [127]. An overview is given by Liu et al. [128]. However, there are some studies dealing with evolving floodplains and the role of individuals [129]. One focus in these models is an analysis of the resilience of the social systems in floodplains [130]. Another focus lays on vulnerability analysis, as exemplarily shown by Turner et al. [131]. The approach is also used to model flood protection investments [132]. The CHANS approach focuses on spatially explicit simulations of changes in systems by considering feedback mechanisms between human activities and the natural environment.

In 2013, the International Association of Hydrological Sciences launched a decade of focused research with the theme “Panta Rhei: Change in Hydrology and Society” [133–135]. Consequently, hydrological science attempted to analyze and model human behavior and their interlinkages with the natural environment, as well as co-evolutionary dynamics. These attempts are often termed as “socio-hydrology”. This new focus aims at understanding the dynamics and co-evolution of coupled human–water systems [136] and the relationships between society and floods [137]. Soon after, conceptual articles followed and sharpened the research topic [138–148]. A review is given by Blair and Buytaert [125].

In parallel, different case studies described typically complex problems in floodplains from the “socio-hydrology” perspective [149–156]. A debate on socio-hydrology describes different points of views and discussions between research groups in this field [157–163]. In the wider field of socio-hydrology, a few studies focused on the dynamic behavior of floodplains as human–water systems [164] and on conceptualizing human–flood interactions [165,166]. The main topic herein is the relationship between the development paths of settlements and the construction of levees. In contrast to the CHANS approach, socio-hydrological models are based on system dynamics, and simulate system behavior mainly in a lumped way (that is, a way that is not spatially explicit). In geomorphology, similar tendencies in capturing and analyzing the co-evolution of socio-natural systems and the effects of human interventions on river morphology can be observed [167–169]. Hydrologic and geomorphic drivers in flood hazard evolution are compared by Slater et al. [170].

The unresolved challenges in socio-hydrology lie in the parameterization and validation of the models [163]. Spatially explicit models for the prediction of future pathways in floodplain evolution

are still lacking [138,171,172]. Furthermore, there is still a lack of models that can predict potential adverse consequences for flood risk due to unintentional developments in the areas protected by levees [164]. This cannot be studied until the models explicitly consider space and time.

In the following sections, I will give a short overview of the three selected approaches that enable the consideration of the interactions between natural processes and human activities and describe the complex behavior of floodplains. I exemplarily selected one top-down modeling approach, one bottom-up modeling approach, and an approach that offers, in my opinion, a promising way to combine the two first mentioned options. The selection of modeling approaches is based on the classification of Kelly et al. [173]. The top-down modeling approaches aim to represent the system as a whole. The system behavior is represented by the interactions between the system components. Its design is mostly inferred by studying the overall behavior of the system. A model designed in this way can produce only deterministic results, and processes within the system are usually hard to analyze. In contrast, the bottom-up approach mainly focuses on representing the processes in a system. The overall behavior of the whole system results from the processes and their interactions. The latter approach is implemented mainly by explicitly considering space and time. A typical example of the first modeling technique is system dynamics. The most typical bottom-up modeling approach is agent-based models. A prospective approach of combining the benefits of both approaches is coupled component modeling.

4.1. System Dynamics

System dynamics (SD) is a computer simulation problem-solving approach with a foundation in the concepts of system feedbacks with the purpose of gaining insight into real-world system behavior [174]. System dynamics is based on the first computational experiments of Forrester [175] and on the system theory of Luhmann [176]. These approaches have recently been used in conceptualizing human-flood interactions [165], in vulnerability analyses [177], in modeling the feedbacks between flooding and economic growth [178], and to analyze upstream-downstream trade-offs in the internalization and externalization of flood risks [179].

However, system dynamic models are in most cases lumped models. Only a few studies deal with a spatial discretization of system dynamic models [180–183]. In flood risk research, these either deal with structural changes in flood risks [174] in general, the management of flood risk [111], or disaster management [184].

These approaches provide a potential for system conceptualization and thus a holistic analysis of floodplains. However, there is still a lack of methods for incorporating physically-based process models and linking them with the other modules in complex models. Moreover, the consideration of changes over time in system dynamic models is still a challenge. As an example, in studying the evolution of the flood risk of a specific floodplain, a modeler would build a system model at the macro level that incorporates the main drivers that change risk, such as river morphology, river engineering works, the dynamics in the exposure of houses, and finally, the risk management strategies. The modeler must know the present state of the system, the changes in these drivers, and the effects of the different risk reduction options. The system dynamics model would then quantitatively simulate the change in the overall flood risk in the floodplain within a certain time period. Thus, the outcome is quantitative, but aggregated in a lumped variable. The processes on the ground, that is, the spatiotemporal dynamics, are not modeled explicitly. However, the adaptive capacity can be studied because of the ability to consider flood risk management options and their effects.

4.2. Agent-Based Modeling

Agent-based modeling techniques (ABM) aim at simulating the behavior and decision-making of individuals (agents) and groups of individuals or institutions explicitly in space and time at the micro scale [125,173,185]. In (multi)agent models, the interactions between the agents are considered as well. The behavior of the agents is mostly determined by a set of rules. Agents can share common resources,

compete, or react to a changing environment. Moreover, agents could be simulated as learning entities. The overall system behavior results in the sum of all actions, reactions, and interactions of the agents. Thus, this approach is preferably used in modeling complex adaptive systems. In hierarchical agent-based models, the effects of regulations by institutions could also be simulated [186]. Another benefit of this approach is the ability to consider time lags, memory, and legacy effects. Major challenges in developing agent-based models lie in their calibration and validation. In regards to flood risk management, agent-based models are being used for simulating the behavior of people in case of flooding. An example is the planning of evacuations [187–189], where pedestrians, cars, and crowding are considered. Another example is the assessment of flood risk management strategies under future climate changes [190]. In this example, institutional behavior is also modeled. In regards to the co-evolutionary dynamics and emergence in floodplains, ABMs can be used to model how individuals and institutions react to a changing environment. Exemplarily, which house owner is taking precautionary measures into account to protect their homes against increasing floods can be simulated. Herein, experience with former flood events, the availability bias, or other incentives could be considered. Furthermore, the role of institutions in changing the environment as a reaction to a flood event could be modeled in space and time. For example, where do governments invest in river engineering works?

4.3. Coupled Component Modeling

Coupled component models (CCM) are composed of specialized disciplinary models representing the parts of the system. Coupled models integrate sub-models to form a model chain that represents a whole system [125]. Synonymously, this type of model is often defined as an integrated environmental model [191,192]. Coupled component models have an advantage in that they are flexible regarding the level of integration, and are relatively transparent because the sub-models are in most cases validated in their specific discipline. Moreover, coupled component models are generally able to combine system dynamics and agent-based models. In such cases, the disciplinary and spatially explicit process models can simulate the (changing) boundary conditions of agent-based models. The outcomes of both results in the system behavior. The design of a CCM can be based on a causal loop diagram of SDs. Hence, instead of using stocks and flows, CCMs simulate the processes directly. However, the sub-models often use different spatial and temporal scales. Thus, the bridging of different scales in model coupling is challenging. Another advantage is that coupled component models can potentially combine both lumped and spatially explicit models. An overview of common coupled or integrated modeling approaches is given by Kelly et al. [173]. However, there is still a lack of integrating process-based models with socio-environmental models. As an example, a few studies showed how to couple system dynamics with agent-based models [193], physically-based models [194], or expert systems [195]. In regards to flood risk analysis, models for weather forecasts are coupled with hydrological models, inundation models, and with flood impact models (for example, flood loss models). An example of a complex modeling chain from rainfall to flood risk is given by Falter et al. [196] or Zischg et al. [197]. In addition, Saint-Geours et al. [198] and Thaler et al. [199] present an approach of incorporating risk management policies in coupled component models.

5. Conclusions and Outlook from a Modeler's Perspective

In this short review, I summarized the literature on modeling floodplains as complex adaptive systems. Beside this, there are other approaches that might be applicable in this context such as Bayesian networks, network theory, or knowledge-based models (that is, expert systems). I focused here on approaches that are applicable in predicting future pathways of flood risk evolution in floodplains. The literature review results in the first overview of modeling floodplains in their complexity and provides a few conclusions for further research that is needed in order to simulate the complex interactions between the natural processes and human actions. Flood risk is determined by several factors, and thus the coupling of models that are specified for selected drivers of flood risk change is needed.

Hitherto, in flood risk research, two main approaches of coupling models prevail. One of the most common approaches is the coupling of different models across specific domains. This is either done in a cascading approach or in a coupled modeling approach. In the first approach, changes in the boundary conditions of the model changes are analyzed from the viewpoint of the impacts to the studied system represented by the model chain. However, the studied system itself, which is represented by the sub-models in the model chain, changes contemporarily with the boundary conditions. In many cases, top-down model chains represent a system behavior that is relatively constant in time. One example of such a shortage is to study future flood risks without implementing the future system status of floodplains with their values at risk and the adaptation of flood risk management strategies over time. Moreover, the development of the studied system over time is influenced by its sensitivity to changes in the boundary conditions. This means that both changes in the boundary conditions and internal changes in the system predetermine the development path of a changing floodplain. Both drivers of change are interwoven, and a sound analysis of changes in complex environmental systems needs to consider them. Thus, a second main approach in model coupling is to study the sensitivity of floodplains. In this bottom-up approach, the focus is laid more on the internal behavior and change of the system rather than on the boundary conditions. In the coupled models, this is studied on the one hand by sensitivity analyses of the sub-modules in an isolated way, and on the other hand by sensitivity analyses of the whole model chain.

While both top-down and bottom-up modeling approaches offer a high potential for the development of methods and tools for the analysis of changes in complex environmental systems, a research gap is identified in bridging both approaches. Therefore, the main aim of future research in modeling floodplains as complex adaptive systems should be to integrate both approaches. This should lead to an extension of the capabilities of coupled component modeling. If the sensitivity of a hydro-geomorphic system is analyzed in detail and a model of adaptive behavior is developed (bottom-up approach), a subsequent analysis of the impacts of changing the boundary conditions (top-down), and consequently, a prediction of future development paths can be done more satisfyingly. This means that changes over time in the boundary conditions meet system-specific sensitivities and adaptive capabilities. Figure 1 schematizes a possible combination of top-down and bottom-up approaches in modeling floodplains as complex adaptive systems with a coupled component model.

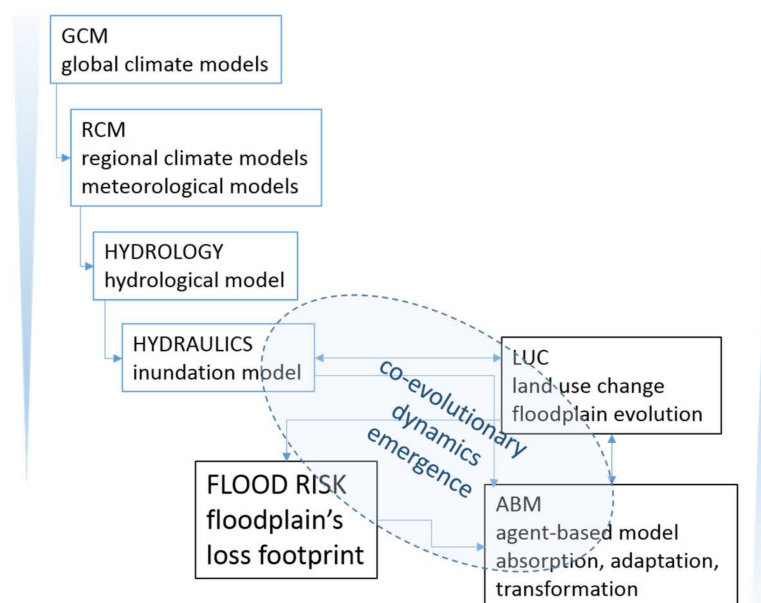


Figure 1. The proposed schema for merging top-down and bottom-up approaches in the framework of coupled component models.

Herein, coupled component models seem to promise the most flexible and robust approach for the prediction of future pathways of floodplain development. This modeling approach is modular; thus, the model chains can be extended step by step with sub-models that have already been validated in their specific domain of application. This modularity makes coupled component models more transparent, robust, and interpretable than lumped specific-purpose models. However, the coupling of already existing models remains a challenge, as they potentially address different scales in space and time. Moreover, coupled component models are preferred, as they consider explicitly spatial phenomena.

Before being applied in floodplain modeling, coupled component models have to be extended remarkably. In my opinion, especially the coupling of process models with agent-based models that simulate the interactions of individuals and institutions with the changing environment, offer a huge potential for extending the capabilities for simulating complex adaptive systems such as floodplains. Thus, the inclusion of the bottom-up modeling approach leads to a more holistic application for prediction purposes than process models alone. The combination of physics-based process models and ABMs offer a thorough simulation of the spatiotemporal dynamics in floodplains. In conclusion, the coupled component models have to be extended with agent-based models representing adaptive behavior sub-modules, and with capabilities for modeling the interactions between the sub-modules, such as feedbacks. This might lead to the capability of modeling adaptive behavior and emergent phenomena.

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